Appendix B

Probability of Failure Due To Internal Erosion

B-1 INTRODUCTION

Failure of the proposed new embankments may occur by piping or internal erosion of materials through defects in the embankment or foundation. Defects created in the new embankment and foundation during consolidation of the underlying peat or other unknown defects may lead to concentrated leakage and subsequently to failure during normal operations.

This section discusses the probability of failure due to internal erosion. The probabilities of failure due to internal erosion for normal operations as reported in this section is a portion of the aggregate probability of failure of the embankments for normal operations.

B-2 METHODOLOGY

The probability of embankment failure due to internal erosion was estimated by developing an event-tree similar to that outlined in USBR (1997).

The event-tree used to represent a failure by internal erosion included the following steps:

1. Initiation of Concentrated Leak Through the Embankment
2. Continuation of Internal Erosion Process Through Unfiltered Exit
3. Progression of Internal Erosion – Ability to Support a Roof
4. Progression of Internal Erosion – Inability to Limit Flows
5. Progression of Internal Erosion – Erodible Soils
6. Unsuccessful Early Intervention
7. Initiation of Breach
8. Unsuccessful Heroic Intervention

Factors affecting the likelihood or unlikelihood of each of the above steps were considered in assigning probabilities based on verbal descriptors. The verbal descriptors used are described in Table B-1 below.

Table B-1 – Verbal Descriptors of Probability

Descriptor	Probability
Virtually Certain	0.999
Very Likely	0.99
Likely	0.9
Neutral	0.5
Unlikely	0.1
Very Unlikely	0.01
Virtually Impossible	0.001

B-3 PROBABILITY OF FAILURE

Seepage forces that might lead to internal erosion can occur either towards the reservoir or towards the slough depending on the operation of the reservoir. During periods of the year when the reservoir elevation is lower than the adjacent slough, groundwater flow and seepage will be from the slough toward the reservoir. During periods when the reservoir is full, groundwater flow and seepage will be from the reservoir toward the slough. The potential for internal erosion occurring when the reservoir is full is less than when the reservoir is empty due to the difference in head between the reservoir and the adjacent slough during those stages of normal operations.

The probability of failure due to internal erosion during normal operations was estimated as an aggregate probability of failure for two water flow conditions:

1) Outward flow toward the slough with a full reservoir (water at elevation +4 ft) and low tide slough water elevation at –1 ft; and

2) Inward flow toward the reservoir with an empty reservoir (water at elevation –15 ft) and tide slough water elevations. Tide slough water elevations corresponding to various flood levels (frequencies) were considered.

The results of seepage analyses indicate that outward flow toward the slough is unlikely due to the limited head difference between the reservoir and the adjacent slough (i.e., the probability of failure due to outward flow is small). For the inward flow condition, the likely and unlikely factors and the assigned probabilities of the event-tree for an entire year of normal operations are discussed in Tables B-2 through B-9 below.

Table B-2 - Initiation of Concentrated Leak

Likely Factors	**Unlikely Factors**
Fibrous peat foundation can crack due differential consolidation Silty sand embankment can crack and shear due to settlement of underlying peat during construction.	Exit gradients determined from seepage analysis are less than would likely cause sand boils or piping.
P = 0.1 Areas likely to crack P = 0.9	

Table B-3 - Continuation of Internal Erosion Process Through Unfiltered Exit

Likely Factors	**Unlikely Factors**
There is no drain under the reservoir side embankment to reduce seepage forces. There is no filter zone located “downstream” of the reservoir side embankment fill	In areas likely to crack (See Appendix C) filter fabric will be installed between the existing levee and new embankment fill. Integrity of filter fabric will be dependent on the amount of deformation.
P = 0.9 Areas likely to crack P = 0.1	

Table B-4 - Progression of Internal Erosion: Ability to Support a Roof

Likely Factors	**Unlikely Factors**
If erosion were to reach fibrous peat foundation, it would support a roof.	New embankment material would not support a roof.
P = 0.5 Areas likely to crack P = 0.5	

Table B-5 - Progression of Internal Erosion: Inability to Limit Flows

Likely Factors	**Unlikely Factors**
	Exit gradient reduced by twenty percent from existing condition by construction of new embankment [1] In areas likely to crack higher potential flows through cracks will be limited by filter fabric
P = 0.1 Areas likely to crack P = 0.1	

[1] Calculated using SEEP/W

Table B-6 - Progression of Internal Erosion: Erodible Soils

Likely Factors	Unlikely Factors
Existing levee materials are variable and include peat clay, and silty sand. Silty sands are erodible	
P = 0.9 Areas likely to crack P = 0.9	

Table B-7 - Unsuccessful Early Intervention

Likely Factors	Unlikely Factors
Long embankments will be more difficult to monitor	Leakage generally accessible on reservoir-side slope Early phases of erosion process can be controlled Assume monitoring will be conducted during and after construction Assume embankments instrumented During construction equipment and materials will be readily available
P = 0.1 Areas likely to crack P = 0.1	

Table B-8 - Breach Initiates

Likely Factors	Unlikely Factors
Silty sand in portions of the existing levee is highly erodible	
P = 0.5 Areas likely to crack P = 0.5	

Table B-9 - Unsuccessful Heroic Intervention

Likely Factors	Unlikely Factors
Head in slough cannot be reduced Embankment materials to fill breach not readily available	
P = 0.9 Areas likely to crack P = 0.9	

The estimated probability of failure for an entire year due to internal erosion caused by inward flow is equal to the product of the individual probabilities in Tables B-2 to B-9. Therefore, the estimated probability of failure due to internal erosion by inward flow during one year of normal operations due to either excessive seepage or cracking is 0.018 percent.

For comparison, in areas where cracks are likely to occur, the probability of failure due to internal erosion increases from 0.018 percent to 4.1 percent if filter fabric is not installed to mitigate piping. This probability of failure was calculated by increasing the probability of the steps listed in Table B-3 to 0.9, Table B-5 to 0.5, and Table B-7 to 0.5. For areas where cracking is unlikely, the probability of failure due to internal erosion decreases from 0.018 percent to 0.002 percent if filter fabric is installed to mitigate piping. This probability of failure was calculated by decreasing the probability of the step listed in Table B-3 to 0.1.

The probability of failure due to internal erosion during normal operations considering both the inward and outward flow conditions were then calculated by weighting the above probabilities by the portions of the year when the reservoir is empty (inward flow) and full (outward flow), as shown in Table B-10. For this study, the probability of failure due to an outward flow is assumed to be 10% of that for the inward flow (0.0018 percent). The calculated annual probability of failure due to internal erosion is therefore 0.0127 percent.

Table B-10 – Probability of Failure Due to Internal Erosion During Normal Operations

Flow Condition	Portion of Year	Annual Probability of Failure (%)	Weighted Probability of Failure (%)
Inward Flow	0.67	0.018	0.01206
Outward Flow	0.33	0.0018	0.000594
		Average Annual Probability	**0.01265**

Similarly, the probabilities of failure for the various flood levels were estimated based on the annualized estimate of probability of failure for internal erosion due to inward flow, and proportioned to their calculated hydraulic gradients. Table B-11 shows the estimates for the various flood levels and the average annual probability of failure due to internal erosion.

Table B-11 – Probability of Failure Due to Inward Flow

Period From (years)	Period to (years)	Annual Probability (%)
0	1	0.018
1	10	0.018
10	150	0.0198
150	450	0.02295
	Average Annual Probability	0.02186

The probability of failure due to internal erosion during normal operations including various flood levels, considering both the inward and outward flow conditions, was then calculated by weighting the above probabilities by the portions of the year when the reservoir is empty (inward flow) and full (outward flow), as shown in Table B-12. For this study, the probability of failure due to an outward flow is assumed to be 10% of that for the inward flow (0.002186 percent). The calculated annual probability of failure due to internal erosion during normal operations including flooding is 0.0154 percent. Therefore, various flood stages increase the probability of failure due to internal erosion during normal operations by 0.0027 percent.

Table B-12 – Probability of Failure Due to Internal Erosion During Normal Operations Including Flooding

Flow Condition	Portion of Year	Annual Probability of Failure (%)	Weighted Probability of Failure (%)
Inward Flow	0.67	0.02186	0.01465
Outward Flow	0.33	0.002186	0.000721
		Average Annual Probability	**0.01537**

B-4 REFERENCES

United States Bureau of Reclamation (USBR), 1997. "Estimating Risk of Internal Erosion and Material Transport Failure Modes for Embankment Dams," Risk Analysis Methodology, Appendix E, Version 2.4, Technical Service Center, Bureau of Reclamation, Denver, Colorado, October 1995, (Revised March 28, 1997).